Integrating iceberg variability in the climate system using the iLOVECLIM climate model

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2016

document version
Publisher's PDF, also known as Version of record

Abstract

This thesis deals with the impact of the Greenland ice sheet, especially its freshwater fluxes, on the northern hemisphere climate during the pre-industrial, the current interglacial and the last glacial. Presently, the Greenland ice sheet is strongly changing and it has changed substantially over the past millions of years in both extension and thickness. These altered ice sheet conditions lead to an altered amount of released freshwater fluxes (calving and runoff), which directly impacts the climate of the northern hemisphere as well as global climate.

Numerical climate models are a powerful tool to investigate the interactions between different climate components. In this thesis, such a model (iLOVECLIM) is used to test the effect of lower/higher temperatures on ice sheets, as well as the impact of growing/shrinking ice-sheets on climate. Yet, in climate models the freshwater fluxes coming from an ice sheet have mostly been parameterized. Therefore, the freshwater fluxes are dumped either directly at the coast or are evenly distributed in the areas where the icebergs are expected to melt. Recent modelling studies, however, have shown that icebergs play an active role in the climate system as they interact with the ocean and the atmosphere. The icebergs impact is due to their slowly released melt water, which freshens and cools the ocean and consequently alters the ocean stratification and the sea ice conditions.

By actively coupling the ice-sheet - iceberg - climate components of the iLOVECLIM model, changes in the prevailing climate conditions affect the ice sheet and consequently the freshwater fluxes, which then impact the prevailing climate. These interactions are treated by the first research question.

What is the impact of icebergs coming from the Greenland ice sheet on the climate of the Mid- to High latitudes and the Greenland ice sheet itself under pre-industrial equilibrium conditions? Do directly applied freshwater fluxes (hosing experiments) have a different effect?

After coupling the iceberg module included in iLOVECLIM to the GRISLI ice-sheet model and closing the water cycle between the ice-sheet - iceberg climate model components, we found that GRISLI satisfactorily computes the calving sites as indicated from present-day observations with a slight underestimation of the calving along the south- eastern margin of Greenland. Also the main iceberg routes are well captured by the model and the icebergs are moved around Greenland and then along North America southward. Yet, the calving amount is strongly overestimated due to the colder than present-day applied climate conditions and the implemented simple calving routine.

Performing sensitivity experiments, we tested the individual role of the different factors that influence the impact of the ice release on the ocean: release of ice discharge as icebergs versus as freshwater fluxes; freshening and latent heat effects. Our results reveal that icebergs enhance the sea-ice thickness around Greenland, which causes cooler atmospheric conditions and a thicker Greenland ice sheet. Dumping the calving flux in the ocean directly at the calving sites, thereby cooling and freshening the ocean locally, produces a comparable climate and ice sheet conditions as the simulation where icebergs are explicitly modelled. The experiment where the ice discharge is released into the ocean at the calving sites while taking up the latent heat homogeneously, underestimates the cooling effect close to the ice sheet margin and overestimates it further away, thereby causing a reduced ice sheet thickness in Southern Greenland. We therefore conclude that the spatial distribution of the take-up of latent heat related to iceberg melting has a bigger impact on the climate than the input of the icebergs melt water. Moreover, we find that icebergs affect the ice sheets geometry even under pre-industrial equilibrium conditions due to their enhancing effect on sea ice, which causes a colder prevailing climate.

In the iceberg model, icebergs are generated daily according to a size distribution observed in one Greenland fjord by (Dowdeswell et al., 1993). However, this distribution may not be valid during different climate conditions. Moreover, the iceberg tracks and consequently the spatial distribution of the icebergs melt water depend on the modelled atmospheric and oceanic conditions. In the second research question we tackle those uncertainties in iceberg modelling.

How sensitive are the modelled climates of the Northern Mid- to High Latitudes and the Greenland ice sheet to the icebergs size distributions as well as variations in the spatial distribution of the icebergs freshwater and latent heat fluxes under different climate conditions (pre-industrial, colder and warmer than pre-industrial)?

Concerning the effect of the oceanic and the atmospheric conditions on the spatial distribution of the icebergs, we find that icebergs that are only moved by the ocean currents stay close to the Greenland and North American coast, whereas the atmospheric forcing quickly distributes them further away from their calving site. This has a direct effect on the lifetime of icebergs, since icebergs, which stay close to the coast reside in generally cooler waters and therefore last up to two years longer under pre-industrial conditions. Furthermore, in iLOVECLIM the local variations in the spatial distribution of melt water due to the application of different iceberg size distributions does not result in different climate states or Greenland ice-sheet volumes, independent of the prevailing climate conditions (pre-industrial climate, warming climate (1120 ppm CO_2 = +4° ,C global mean temperature over 1000 years) or cooling climate (70 ppm CO_2 = -4° ,C global mean temperature over 1000 years)). This indicates that local differences in the distribution of iceberg melt fluxes do not alter the prevailing northern hemisphere climate and the Greenland ice sheet under equilibrated conditions and continuous supply of icebergs. Also, we find that the applied radiative forcing scenarios have a stronger impact on climate than the initial size distribution of the icebergs.

Proxy data indicates the occurrence of periods with enhanced iceberg discharge from the Greenland ice sheet during the Holocene (the past 11.700 years), but the mechanism behind these events is still a matter of debate. So far different variations in the incoming total solar irradiance (TSI), volcanic eruptions and the combination of internal climate variability and external forcings have been suggested as cause of the enhanced iceberg discharge. We investigated the impact of the mentioned forcings on the calving flux of the Greenland ice sheet over the past 6000 years.

Can we reproduce the centennial-to-millennial scale iceberg events during the Holocene in our coupled climate ice-sheet iceberg model? What are the mechanisms behind these enhanced iceberg events?

We performed ensemble experiments to test the impact of the TSI forcing (no variations in TSI, variations of $\pm 1 \mathrm{W\,m^{-2}}$, variations of $\pm 5 \mathrm{W\,m^{-2}}$), as well as the effect of volcanic eruptions. Furthermore, an experiment was done with idealized sinusoidal TSI variations of $\pm 4 \mathrm{W\,m^{-2}}$ and to test internal ice-sheet variability we performed one additional experiment with fixed climate conditions. All the model runs displayed prominent peaks of enhanced iceberg melt flux (IMF), independent of the chosen experimental set-up over the past 6000 years. The conducted spectral analysis of the model run with fixed climate conditions displays one significant peak of about 1500 years due to internal ice sheet variability. This frequency is modulated to 2000 and 1000 years in all the experiments with a coupled climate ice sheet due to interactions between the model components. Moreover, we analyse the effect of minimum TSI events on the timing and occurrence of enhanced IMF. In the experimental set-up that was forced with idealized sinusoidal TSI variations, we find a significant occurrence of an increased iceberg melt flux about 60 years after the minimum TSI value. Yet, we also see a significant time lag of 80 years between reconstructed TSI minima and the simulated enhanced iceberg melt flux in some of the experiments without TSI forcing, which indicates that the relationship between TSI and IMF is due to internal dynamics of the coupled system. From our experiments we conclude that internal ice sheet variability seems to be the source of the multi-century and millennial-scale iceberg events during the Holocene.

Even more prominent iceberg events occurred during the Last Glacial, so-called Heinrich events. These events are represented by a strong increase in ice rafted debris found in marine sediment cores. Yet, their signal is not directly recognizable in the oxygen isotopic composition recorded in the calcite of planktonic foraminifera, which depends on both the prevailing temperature and isotopic composition of seawater. Explicitly including the oxygen isotopes in *i*LOVECLIM enables us to investigate the impact of icebergs on the 18Ocalcite signal.

What is the impact of the duration of Heinrich event-like iceberg discharges on the North Atlantic Ocean? How do changes in ocean temperatures and $\delta^{18}O_{calcite}$ due to the icebergs melt water impact the $\delta^{18}O_{calcite}$ recorded in proxies at various locations?

We conducted three experiments with an iceberg forcing of 0.2 Sv (1 Sv = 10^6 $m^3 s^{-1}$) to investigate first, the impact of the duration of a Heinrich event-like iceberg forcing on the North Atlantic Ocean and second, the mechanisms behind the simulated $\delta^{18}O_{calcite}$ pattern. This iceberg forcing was applied for 300, 600 and 900 years, respectively and in iLOVECLIM the response of the Atlantic Meridional Overturning Circulation strongly depends on the duration of the Heinrich event like iceberg discharge. The timing of the first response of the ocean conditions to the iceberg forcing coincides between all the experiments in the various regions and happens within 300 years. Moreover, we find two main patterns in the modelled $\delta^{18}O_{calcite}$ signal. On the one hand, the central and northeast North Atlantic regions display almost no response in $\delta^{18}O_{calcite}$ to the applied iceberg forcing since the changes in sea surface temperature and $\delta^{18}O_{seawater}$ compensate each other or, if the forcing is applied long enough, a delayed response is seen. On the other hand, we show that in Baffin Bay, the Nordic Seas and the subtropical North Atlantic the change in $\delta^{18}O_{seawater}$ exceeds the sea surface temperature signal and there the $\delta^{18}O_{calcite}$ pattern closely follows the $\delta^{18}O_{seawater}$ signal and displays a continuous decrease over the length of the Heinrich event with the minimum value at the end of the iceberg release. The comparison of the model experiments with four marine sediment cores indicates that the experiment with an iceberg forcing of 0.2 Sv for 300 years yields the most reasonable results.

The coupling of the ice sheet iceberg - climate model enabled us to investigate the impact of icebergs on the Greenland ice sheet and the northern hemisphere climate during different time periods. We conclude that icebergs have a direct impact on the Greenland ice sheet and that internal iceberg variability appears to be the mechanism behind the Holocene iceberg events. Moreover, the implementation of isotopes in iLOVECLIM allowed us to analyse the effect of a Heinrich event like iceberg discharge on the simulated $\delta^{18}O_{calcite}$ pattern to facilitate the

interpretation of Heinrich events in marine sediment cores. The comparison of the model experiments with four marine sediment cores displays the best agreement if an iceberg forcing of 0.2 Sv for 300 years is applied.